Norbert Wiener and the Age of Controls, Communications, and Cybernetics—Animal and Machine—in Electrical Engineering [History]

Norbert Wiener and the Age of Controls, Communications, and Cybernetics – Animal and Machine – in Electrical Engineering by Marcelo Godoy Simões

My antecessors were fishermen familiar with rivers and the ocean, also from rural areas, in the state of São Paulo (Brazil). Since I was a kid, I used to go fishing with my father, uncle, cousin, my grandmother sometimes joined us – fishing in rivers, lakes, reservoirs, and on the sea. We used to go to Santos, a famous city that made Pelé famous when he played for the local football team. We hired a boat to take us fishing, mostly at the end of the day and sometimes spending the whole night. I remember observing how the helmsman would steer the boat, starting with a slow engine speed, after the shore waves the engine would be full blast. He would be looking at the horizon, destination was further than the curvature of the Earth. To me was magic how he knew the path, and by just shifting the rudder left and right, we would arrive at our destination, sometimes the ride was quick as 15 minutes, in some places we would have to go by boat for almost one hour. Adult explanations were those conjectures to distract children, talking about the compass, look at the stars, a fisher would know the waters; fisherwoman, fisherfolk and fisher are all same as fisherman, and any gender who fishes is not really concerned with pronouns when fishing. There was no GPS at that time. Big boats would have a nautical chart, but the small ones who we used to take, not even a map, all was in the mind of the pilot, and in my 9 years old self I was puzzled in how just knowing and moving the rudder with simple lefts and rights would put us on a path to arrive at our destination ?

When I started my 7th grade, I definitely knew that I loved Math and Sciences, l started to pay attention to basics of electricity, radios, TVs, how the electric shower would work, and I even opened the back of our RCA victrola where I was mesmerized with those glowing vacuum tubes and the smell of heat in that wooden structure. My cousin, electrical engineer, would explain to me many things, and there was a time he told me some interesting ideas about control systems. I tried my best to understand, but the concept of feedback as related to how the rudder was moved left and right was still not clear. He gave me an example of how the water reservoir in my house would control the amount of water, but at the same time discussed about the temperature of the shower, somehow, I grasped that steering a boat could be conceptualized that commanding the rudder, was a correction. To me that was new – the helmsman would compare an imaginary straight line along the boat, and look to something he knew as a mark, it could be a rock, an island, at night it could look to a star, the trajectory of the boat should be adjusted by a difference, little pluses and minuses, of the deviation from a mark compared to the straight line of the boat main axis. The rudder moves away the water under the boat, making a higher pressure in one side, pushing the back of the boat to the right or to the left. This would what my cousin said a closed loop control, but in other situations he was also talking about closed loop control, for example about the tuning of a radio on the dial. I was 13 years old – how could I possibly understand enough Math and Physics behind these concepts ?

I got older, more electronics magazines trying to learn audio amplifiers, paying attention, there was always the concept of 'feedback' the word is '*realimentação*' in Portuguese. During my bachelor's degree, I was admitted to the Electrical Engineering department in the second year of the university, in the third years I joined the electronics coursework. Learning theories, laboratory experiences, fascinated with radio and TV circuits I learned about oscillators, transistors and amplifiers, feedback was always how they would improve the circuits, in my fourth year of engineering I had strong engineering math focused courses on Control Systems, Linear Systems, Signal and Processing, making further impact on me, on my fifth and last year in my engineering degree I decided to move on the telecommunications area because it had more analog control and transistorized circuits for high frequency applications, by then I started to have the maturity to look back to my 13 years old self, by then 23 years old young engineer, to grasp how my curiosity of how a fishing boat pilot could steer towards a place on the ocean to spend a night fishing, how closing the loop could be accomplished, things flipped my mind when I took for the first time in my 10th semester in EE a course on power electronics, which defined my career. When I was around 30 years old there was a TV ad, from Mercedez Benz and their advanced car suspension technology, with chickens keeping their eyesight when moved up and down, left and right, jerked, people would then believe how Mercedez Benz would have *'Awesomely Chicken Level Standards'* embedded in their car technology. In this article, I am discussing how Control Systems, starting with Maxwell, became elevated in shaping our 20th century through Cybernetics – with the geniality of Norbert Wiener. ***~Raconteur MGS***

Electrical Engineers study dynamical systems: those evolve throughout time in a deterministic way. Most often they are modeled based on laws of Physics, Chemistry, Science, Mathematics, and Economics; however, it is possible to model on previous data or heuristic rules. Engineering and technology is about comprehension and understanding. We want to know the flow of electricity, the motion of a car, what keeps an airplane flying, how electrochemistry in a battery works, how hydrogen goes through a membrane in a fuel cell producing electricity and heat. Also, about balance of systems as well, how population of wolves would stabilize an ecosystem, how goods and prices are related in an economy based on inflation, how ballast and air pressure would keep a submarine under water. Concept of feedback for single or multi-input multiple-output problems became center-and-front throughout the 20th century. After closed-loop control and stability were approached, there was an enhancement of understanding Biological processes, Medicine, Psychology, Social Sciences, even Agriculture, Farming and many other fields. The level of glucose in humans is now understood by Medical Doctors as a negative feedback, when the glucose is high, the pancreas releases insulin make the sugar in the blood to go down, and health care providers evaluate equilibrium in several blood test data analysis: how substances in the blood, such as oxygen, calcium, sodium, potassium, number of red and white cells, are related to blood pressure, heart beating, pupil dilation, breathing are interrelated in the homeostasis and equilibrium of life conditions. Negative feedback has become the way to evaluate, any positive feedback may indicate problems, requiring a short-term or a long-term need of interventions, precautions, and avoiding collapse situations for humans, machines, processes, and nuclear power plants.

During the first few years of the 20th century, it was part already of physicists and electrotechnologists that feedback would enhance telegraphic and radio transmission. Amplifiers made of the new vacuum tubes could be stabilized for operation with feedback. Such concepts were initially developed by James Clark Maxwell, who became interested in another James' work –James Watt (1763-1819)– who controlled a steam rotating machine with a valve commanded by a flying ball with two arms, a kind of a pendulum adapted for actuation on the steam inflow. James Watt also developed intriguing closed-loop mechanisms, approximating straight lines with rotating joints, they are still useful for designing walking and hopping robots, linear haptic interfaces, origami-based mechanisms and deployable linkages. Mechanical engineers have been historically working on these linkages convert rotary motion to linear one, initially in steam engines. The synthesis of four-bar linkages has been of interest to industrialists (prequel engineers) since the 1800s, due to their simple architecture and rich design space; for example, a pumpjack's main mechanism (reciprocating piston pump in an oil well) is a four-bar linkage.

James C. Maxwell became interested in studying the rings of Saturn, and thought on applying such understanding to mathematically analyze speed controllers, particularly approaching the operation of Watt flying balls rotating actuator. He wrote a 14-pages paper "On Governors" in February 20th 1868, it was quickly published in March. He made analysis of a driving power (P) and a given load torque, defined in the article as a resistance (R), which was the resulting shaft motion on a viscous fluid, or air, a dragging force opposing the motion of such a shaft. Applying Newton's laws on a rotating shaft he wrote the equations for a necessary effort (F) to change the angular velocity (V) on such a shaft, such as F(dx/dt -V). Then he would assume a typical valve or governor regulating the keeping by the second order derivative of the angular velocity multiplied by the moment of inertia,

balanced by the driving power P which was subtracted from the viscosity, or dragging effect (R), minus the amount of needed driving power quantity F(dx/dt -V). Therefore, if P is increased or R is diminished, the velocity will increase, and the opposite as well. By making assumptions of such a velocity to be desired to settle down in equilibrium, he discussed a possible steady-state error from the input reference, also assuming disturbance on the driving power, or further dragging probably proportional to the speed. In such a paper he evaluated, from simple to more complicate structures, also describing a liquid in a tube revolving about a vertical axis. His formulation is easy to be understood today as a baseline for a State Space synthesis, maybe for a possible pumping up water for a reservoir, perhaps indicating he was thinking on some kind pumped hydro type of energy storage, but not clearly pointed out as such. He described based on mechanical systems terminology; he called regulators and moderators, mentioned enhancements invented by Jenkin and used by Siemens, with a centrifugal rotating piece, containing an appendage of a loose wheel, which would maintain the rate of correction, such an appendage would keep an internal energy stored, proportional to the integral of the error in the set-point. Maxwell defined in his mathematical formulation, how a set-point applied to a negative summer (with negative feedback) would make the proportional and integral or the error of velocity to drive the shaft, establishing the principles of PI control, which is the basic foundation block of control systems. He did not use any block diagram, just mathematical descriptions. He continued further in his article, making combined differential equations, arriving to a 3rd order, also simplifying a 4th order to become 3rd order, approaching possible exponential responses, assuming the roots of such a cubic polynomial. By the page #10 of such a 14-pages article, he found necessary conditions for stability. But he was not sure if those conditions would be sufficient for really making the system stable. But in such seminal work, Maxwell placed *stability* as the core of his analysis, making a distinction of moderators, where the correcting torque would be proportional to speed error, on the other hand a governor would also contain a term proportional to the integral of the error, he observed mathematically that exact speed regulation, with zero steady-state error was possible, when minimizing the integral of the speed error, with a linearization of the equations of motion through the determination of the algebraic solution of the roots of a polynomial, which is now called characteristic polynomial. He mentioned that it should have negative real parts, similarly to his investigation on Saturn's rings, which were possibly based on the work by Edward Routh who provided a solution, nowadays called as Routh-Hurwitz stability criterion. This was the birth of PI control, in a paper written by J. Clerk Maxwell, but it became overlooked, because Maxwell made further and beyond impact in Electromagnetism, with his original equations of electromagnetic fields – those became synthesized through a new formulation of multivariable calculus and operators by Oliver Heaviside, Einstein was already alive, and too many scientific and engineering discoveries were happening in a slow pace communications world, as opposed to our current one.

Norbert Wiener decided to use science and technology to win WW II. He made it possible that humans and systems could be tackled in a multi-discipline approach. Radars could detect attacking airplanes, but as soon as the detection was available, the planes would be in an unexpected position. Then he did many experiments, interviewed pilots, military personnel, and brought together *behaviorism* in a mathematical formulation. His algorithm, now called Wiener Filter would predict where those planes most likely would be after detection, also considering the delay in the reaction. He is the father of today we call *Control Systems* although his original perspective was more

encompassing through a signals/systems/math/behavior umbrella. He presented an unifying perception of circuits, control, communication, and information theory, in his book published in 1948 "Cybernetics, or Control and Communication in the Animal and the Machine"; a theory of everything, based on systems, inputs, outputs, information flow, noise, stability, feedback, triggering to influence the next three or four generations of academics, researchers and scientists — a scheme for predicting the future, as best one could do, on the basis of incomplete information about the past. It was statistical in nature with modeling information for removing noise. His approach was based on earlier work on integral equations and Fourier transforms — becoming the foundation of random processes and stochastic systems. Norbert Wiener baptized the emerging field of control and communication as *Cybernetics* from the Greek $\kappa\upsilon\beta\varepsilon\rho\upsilon\eta'\tau\eta\varsigma$, such a "Cybernetics" is derived from the Greek '*kubernetes*', translated as *steersmanship*', meaning the understanding and skills required to successfully steer a ship to a desired destination. Therefore, my young self-curiosity on how a pilot driving a boat, correcting the rudder with little movements, eventually shows as the core of the original name by Wiener on Control Systems after all. Norbert Wiener made *'cyber'* part of our daily contemporary life, the concept becamean ever-encompassing terminology: from cybernetics, to cyborg, then, cyberobotics, cyberspace, cyberculture, cyberpunk, cyber-physical-systems, cybersecurity. In addition there are terms such as cybernating, cybercafe, and cybersex. It has been the most enduring and comprehensive multidisciplinary terminology, a trend of words in Google shows an exponential increasing presence for the past 85+ years.

During World War II, Wiener's work on automatic aiming and firing anti-aircraft guns motivated him to investigate information theory done independently of Claude Shannon (who also deserves a narrative of his own contributions). The Wiener filter was initially published in 1942, as a classified document, supporting modeling and estimation to minimize the noise present in a signal, by comparison with a model-reference of a desired noiseless signal. In order to predict position of German bombers from radar reflections, it was required to forecast the new position. By the time the shell reaches the vicinity of the target, the target would have then been moved, changed directions – Wiener considered muscle response of pilots, interviewed pilots to have scenarios on what would be their next decision immediately after being detected. He blended information and control in a way that would make the dawn of Cybernetics, upscaling basic feedback previous ideas. It is part of lore, that American guns fitted with Wiener filters, would shutdown 99 out of 100 German bombers, as they entered Britain from the English channel on their way to London, but is not possible to ascertain such an efficiency.

Wiener acknowledge Maxwell was the father of control principles – PID control is still taught as a significant concept in contemporary engineering. With the increasing opening of new electrical engineering departments after WWII, the modern automatic control, state-space oriented, multivariable control systems, classic and modern controls were established from 1950s towards 1980s. For students in electrical and electronics engineering, it became and intertwined area of math, signals, systems, and digital algorithms. Education and research on this area has been influential for all generations, supporting that electrical engineers should be capable to design, even with only pencil and paper, compensators such as proportional-integral-derivative (PID) lead, lag, and lead-lag. Most of the textbook classic problems would be about SISO (single-input/single-output) control structures, the classic design based on Nyquist, Bode, and Root-Locus. However,

MIMO using state space approach became widely adopted, then most advanced curriculums would cover advanced mathematical concepts and non-linear systems.

Books and courses have been published since 1950's to make students understand how a suitable closed loop controller could be designed, analyzed and built, initially based on analog control. With primordial mainframes, then desktops and microprocessors, made people in the 1970's to discretize control laws, using straightforward Euler's trapezoid methodology, then other methdologies. Some theoreticians would prefer the utilization of Z-transforms, although not necessary for practical implementations. Typically control systems have a fundamental approach in the mathematical description of closed-loop properties in terms of open-loop characteristics. It also incorporates a main plant or main system model, based on ordinary differential equations, Laplace transforms and frequency domain. From basic principles it is not so difficult to define disturbance rejection properties, steady-state error performance, sensitivity and parameter variation. Good control system designers also know how to incorporate feedforward or mitigation right-half-plane zeros, non-minimum-phase systems, industrial processes with transport delay, for analog or digital implementation.

After the II WW Norbert Wiener became famous. He helped MIT to recruit a group in Cognitive Science, researchers in neuropsychology, mathematics and biophysics of the nervous system. Warren Sturgis McCulloch and Walter Pitts joined MIT and became the fathers of Artificial Neural Networks. They made pioneering contributions to Computer Science and Artificial Intelligence. The McCulloch and Pitts paper is the inception of two fields, the theory of finite state machines as a model of computation, as well as the field of artificial neural networks, which has been rebranded in the past few years as Deep Learning.

The history of Neural Networks and Fuzzy Logic could be a future article. But it is important to have a parenthesis here, since neural networks, inspired by the studies for understanding the biological nervous system, has a first relevant reference on the physiology and psychology studies related to the structure and function of the brain, published by William James. After McCulloch and Pitts published their seminal paper in 1949, Donald O. Hebb published a book as Hebbian learning. In 1958 there was a landmark paper by Frank Rosenblat defining a neural network structure called perceptron, simulated on a IBM 704 computer at the Cornell Aeronautical Laboratory and for the first time it became a fact that such a perceptron could be a "leaning machine." In 1960, Bernard Widrow and Marcian Hoff published a paper where they simulated neural networks in computers, and also had implemented their designs in hardware. Widrow and Hoff introduced a device called an adaline (for adaptive linear). An adaline consists of a single neurode with an arbitrary number of input elements that can take on values of plus or minus one and a bias element. Before being summed by the neurode summer, each input, including the bias, is modified by a gain. The Widrow-Hoff algorithm is a form of supervised learning that adjusts the weights according to the size of the error on the output of the summer. In 1969 the book 'Perceptrons' by Marvin Minsky and Seymour Papert cooled off the neural network community their writing style was acid in claiming that most of the research about neural networks was "without scientific value." They showed that the two-layer perceptron was rather limited because it could only work problems with linear separable solution space. There was no effective algorithm to train a network with three or more layers until the

derivation of the backpropagation algorithm later. After that book, virtually all research funds for neural network dried up. The revival in the field came with the research conducted by John J. Hopfield in the beginning of the 80's, leading to today's Hopfield network, also CMAC by J. Albus, and the Teuvo Kohonen self-organizing map unsupervised learning model initially published in 1982. What primarily influenced people about the capabilities of neural networks was the discovery of the backpropagation algorithm. It was found by Paul Werbos, Dave Parker, and independently rediscovered and popularized around 1985 by Rumelhart, Hinton, and Williams. Neural networks had a second birth in 1985.

Nobert Wiener developed the theories of cybernetics, robotics, computer control, and automation. He was so advanced in his ideas that he wrote about modeling of neurons to John von Neumann, documented in a letter dated of November 1946, with his theories and findings with other researchers, on such an encompassing cybernetics approach. Norbert Wiener included Soviet researchers in his correspondences, one important one was Andrey Kolmogorov, who published a paper in 1938 establishing theorems for smoothing and predicting stationary stochastic processes. They developed mutual interest on studies of systems capable of receiving, storing, and processing information so as to use it for control, even helping the setting up of neural networks initial foundations. Obviously, during the Cold War environment the Wiener's acquaintance with Kolmogorov caused him suspicions by the US government, typically orchestrated by the FBI director in charge during those times. Wiener was a strong advocate of automation to improve the standard of living, and to end economic underdevelopment. His ideas became influential in India, whose government he advised during the 1950s. After the war, Wiener became increasingly concerned with what he believed was political interference with scientific research, and the militarization of science. His article "A Scientist Rebels" from the January 1947 issue of The Atlantic Monthly urged scientists to consider the ethical implications of their work. After the war, he refused to accept any government funding or to work on military projects. Wiener's beliefs concerning nuclear weapons and the Cold War contrasted with those of von Neumann. The advent of cybernetics made psychological, and behavior approaches in neural networks spin off and augment the rise of cognitivism. Then scientists in different areas would be considering internal states of mind, thoughts and consciousness. Multi-domain linguistics such as Noam Chomsky, plus emerging of neural sciences would bridge mathematics, biology, social sciences, medicine and technology. Conferences, meetings, publications, summer schools, symposiums, research centers became established towards the end of 1990's.

Cybernetics which was a theory of everything inverted inside-out to become an everything-through-a-theory, an interplay of technology, society and the environment, approaching complex systems through processes like feedback and communication, engineering systems and systems engineering.

The Wiener filter mathematics was a reference for the Kalman filter, applied for advanced problems. In about the same time a young professor , Lotfi Zadeh co-authored with Charles Desoer, 'Linear System Theory: The State Space Approach', with foundations for system analysis and control. Rudolf Kálmán was a colleague in the same university as Zadeh – Kálmán enhanced and improved the Wiener filter, the Kalman Filter would require in-depth mathematical modeling – Zadeh soon realized that another direction would be effective, by assuming that as more complex a problem

goes, more uncertain becomes parametrization and modeling, to the point of not having any longer a physical meaning in all the mathematics. Therefore, Cybernetics-Zadeh thought on Computing with Words. He wrote a seminal paper in 1965 on fuzzy sets, showing how to replicate human-like reasoning and heuristics, giving birth to the Mathematics of Fuzzy Set, such a theory became fuzzy logic control and fuzzy modeling. It is a different path of theoretical mathematics for modeling systems for designing a control, it is based on modeling how human operators with rules of operation, or data from previous control batches could be used to design a rule-based algorithm instead of a mathematical compensator.

Catherine Everit Macy Ladd was an American philanthropist who founded and endowed the Josiah Macy Jr. Foundation, in honor of her father. The Cybernetics conferences were held between 1946 and 1953, motivated by Lawrence K. Frank and Frank Fremont-Smith of Macy Foundation. Warren McCulloch was the Chair of this set of conferences, with responsibility to ensure disciplinary flow. Cybernetics were particularly complex as a result of bringing together the most diverse group of participants of any of the Macy conferences. The principal purpose of these series of conferences was to set the foundations for a general science of the workings of the human mind, organized studies of interdisciplinarity, spawning breakthroughs in systems theory, cybernetics, and what later became known as cognitive science. Norbert Wiener knew that it was important to have a wide variety of experts, he engaged in yearly conferences called as Macy Meetings, the participants sought interactions in fields of anthropology, linguistics, mathematics, computation, sociology, psychiatry, psychology, neurology, biology.

Do you remember the TV commercial in the 90's where chickens recorded in conditions that would make them show stable, they would be moved up and down, rotated slightly, jerked, but their eyesight would stay at a constant level ? Such a TV ad from Mercedez Bens on a primetime TV commercial was depicting how their car suspensions would achieve standards of excellence in engineering, probably at a majestic chicken-level-standards. Control systems became by then a TV ad commercial propaganda.

We currently have many scientific computational platforms. Students click and drag, point and press enter, selecting menus, and blindly making model-reference and parameter-estimation for control applications in routine school homework. Probably our current generation is already taking for granted the depth and beauty of Cybernetics, Systems, and Control Approach. As we admire 'influencers', *social media providers of content*, maybe we should also think of Norbert Wiener the major Analog and Digital Influencer. There has been scores of thousands to million people who learned and used the theories developed by and after Norbert Wiener, faculty, students, engineers. We have to be aware that Control Systems, as an area of expertise is not 100 years old yet. Cybernetics is doing well and alive, understanding technologies, their interactions with society and environment. We now need a sustainable society, solutions for of smart and cheap electricity, electric mobility systems, water systems, food cycle, upscaling based on a market not dominated by multinational control. Let us work to mitigate gender and socio-economic inequalities. Cybernetics today associated with Circular Economy aligns Sustainability, towards a fair context. As Norbert Wiener envisioned: a motivation for next generation to move forward on and upwards – change is always a constant.

"Cybernetics looks at the design and development of renewable energy systems like hydropower or battery storage and seeks to uncover the impact on groups and environments that may have been outside the initial system design" ~Professor Katherine Daniell, School of Cybernetics at the Australian National University.

Thank you for reading "*The Elektron Whisperer*" (TEW) column by Marcelo Godoy Simões, **see you next time.**

To Probe Further

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